Numerical validation of a near-field fugitive dust model for vehicles moving on unpaved surfaces

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Abstract

Vehicles moving on unpaved surfaces can be significant sources of fugitive dust emissions. The performance of vehicle operational characteristics as well as evaluating vehicle dust mitigation components including filters, radiators, seals, and windshields require models for the behavior and transport of emitted fugitive dust. Much of the work on modeling fugitive dust emissions from vehicles have focused on large scale atmospheric transport for environmental quality purposes. In this study, however, we present a dust emission and transport model suitable for modeling near-field effects of fugitive dust emissions. The presented model is validated numerically for the prediction of dust plumes in a region near vehicles through a careful comparison to the available experimental data. This model provides, for the first time, a validated dust emission and transport models suitable for the near field of moving vehicles. The weakness of the current near-field dust emission and tranport technology is also discussed.

KEY WORD: FUGITIVE DUST EMISSION, COMPUTATIONAL FLUID DYNAMICS, MULTIPHASE FLOW

1 Introduction

Particles suspended in air by vehicular movement on paved and unpaved roads are a major contributor to fugitive dust emissions, which in turn can have significant impact on many aspects of vehicle performance. Scattering caused by suspended dust particles

and dust deposition on wind shields and mirrors may can impair visibility, especially in convoy types of settings. Operationally, dust can be ingested by the engine and power train, increasing maintenance expense and reducing vehicle life-time. In commercial applications, the transport of particulates around a vehicle is of particular interest in determining vehicle soiling. Therefore, accurate prediction of dust emission and transport in the near field of moving vehicles is needed to evaluate the impact of dusty environments on many aspects of vehicle performance.

There are a number of challenges involved in the modeling of dust emission and transport caused by moving vehicles traveling on unpaved roads. First, the dust generation mechanism is dependent on complex phenomena that occur at the contact between the vehicle tires or treads and the dusty surface. These phenomena includes the process of crushing large particles into smaller pieces by the vertical pressure of the wheel and then the transport of the crushed particulates by the tire due to horizontal friction and, finally, the ejection of particulate matter into the air due to centrifugal force. Saltation, which involves the effects of large particles bouncing off of the road surfaces further disturbing the dusty road substrate, is another dust generation mechanism that probably plays a non-negligible role. Some discussions of these dust generation mechanisms can be found in the literature [26, 2]. The amount of the dust emitted into the air by these actions depends on many factors such as dust particle properties (size, density, stickiness, etc.), environment conditions (wind speed,etc.), soil conditions (silt content, moisture level, etc.) and vehicle features (vehicle velocity, weight, dimension, number of

the wheels, etc.). There have been many experimental investigations of the relationship between the magnitude of dust emission and the above factors. Experimental methods include utilizing upwind/downwind dust flux tower measurement system [8, 7, 32], filter-based gravimetric techniques [29, 30], field wind tunnel [18, 24, 6] and the optical remote sensing method [1]. The U.S. Environmental Protection Agency (EPA) has collected and compiled the dust emission factor information gathered under different field conditions. The data and dust emission models are documented in the *Compilation of Air Pollutant Emission Factors* (AP-42) [29, 30, 28]. It has to be mentioned that most experimental work on dust emission induced by vehicles had an objective to model dust emissions as line sources for air quality modeling and so near field collection of data was not a priority. For our application in which the vehicle performance is the main concern, data collected close to the vehicle are needed. However, experimental data that provide detailed near-vehicle measurements of dust concentrations is extremely limited which limits the extent to which near field dust emission and transport models can be validated.

As for modeling of dust emission and transport in the near-vehicle region there has been relatively small amount of work described in the open literature. Most of this work focused on real-time realistic visualization of vehicles such as the numerical models developed at George mason University[2, 3]. Their model focused on representing vehicles in a virtual environment and required a compuatationally efficient model since interactive graphics required the model operate faster than physical time. As a

result, their numerical models were highly simplified, and the simulation results were not validated by any experimental study.

Turbulence provides another challenge in the modeling of dust transport around the vehicle once it is emitted into the air. Once in the air, the dust is scattered by small scale turbulent eddies that form in the vehicle wake as well as large scale turbulent eddies that are superimposed from the ever present atmospheric boundary layer (ABL). Since these features play an important role in accurately describing the mixing and dispersion of dust particles, accurately capturing the ABL is an important component of modeling dust transport about moving vehicles. In our present simulations we model the turbulent eddies using a Reynolds Averaged Navier Stokes, RANS, approach and the scattering due to turbulence is modeled as a stochastic forcing term applied to the particles. Care must be taken to accurately model the ABL. In particular, it can be challenging to recover an ABL profile with standard engineering RANS turbulence models. For our study we utilize the approach that has been shown to sustain an ABL profile for stable atmospheric conditions over a long fetch [21, 33]. This method utilizes a modified surface roughness factor along with an imposed stress boundary condition at the upper boundary to create a correct ABL profile that is sustained over long distances. The effects of turbulence on the dispersion of dust particles have been well studied[12, 25, 19, 4, 22]. For our simulations we model turbulent fluctuations using a first order Markov process as described by Zannetti[35].

We utilize the verified production Loci/CHEM multi-physics CFD code[31, 14] to

simulate the dust emission and transport about a movin vehicle in this study. The CHEM code is a robust highly parallel solver that provides a variety of turbulence models and Lagrangian particle models that are needed to model the physics of dusty flows. In addition the solver provides a flexible mechanism, through the Loci framework[36], for extending the models provided by the baseline CHEM solver. In the following sections we describe the development of specialized models for the emission of particles and their transport and dispersion by the turbulence in the vehicle wake and ABL. We study the sensitivity of the model to source locations of particles as well as particle size distributions. Finally we provide a careful comparison between the numerical model and experimental data providing one of the first attempts at validating a numerical model for the near field dust transport around a moving vehicle.

2 Numerical Simulation Models

In this study, numerical simulations were carried out for the investigation of fugitive dust emission and transport around a moving vehicle. In order to accurately capture the dispersion of the fugitive dust emissions the turbulence of the atmospheric boundary layer must be considered. When using engineering level RANS based turbulence models special care must be taken to ensure that the atmospheric boundary layer is sustained over the simulation domain. The failure of RANS based models with out proper treatment to accurately capture the ABL has been described in the literature[21, 33]. For our simulations we use the method proposed by Richard and Hoxey [20] whereby

the ABL is sustained by utilizing an appropriate surface roughness parameter on the ground along with an imposed stress boundary condition on the upper boundary. We implement these schemes using Menter's baseline (BSL) turbulence model[16] and in separate studies find that the approach is effective at maintaining the ABL over the domain sizes considered in this study which are on the order of a few dozen vehicle lengths.

We employ the Lagrangain particle tracking method to compute the transport of the fugitive dust emissions. Since the RANS turbulence models do not resolve the turbulent eddies, the Lagrangian particle tracking method will not recover the dispersion that these eddies cause. In order to correctly reconstruct the scattering effects of the modeled turbulent eddies we employ a stochastic model of the turbulent fluctuations[34, 22, 27]. In particular we use the method of Zannetti[35] whereby the turbulent velocity fluctuations, $\mathbf{u}'$, are modeled as a simple first order auto-correlation Markov process. In this formulation, turbulent fluctuation, $\mathbf{u}'$, is expressed as:

$$\mathbf{u}'(t_2) = R_L(t_2 - t_1)\mathbf{u}'(t_1) + \mathbf{u}''(t_2) \tag{1}$$

where $R_L(t_2 - t_1)$ contains the auto-correlation with lag $\Delta t = t_2 - t_1$ of the $\mathbf{u}'$ components where $\mathbf{u}''$ is a purely random vector. Using this method the perturbation of each particle is independent and not affected by the position of other particles in the flow. Therefore, the numerical performance is fast since no special interactions between particles and fluid are required. The auto-correlation of the Lagrangian velocity, R_L can be related

to Lagrangian time scales, T_L by

$$R_L = exp[-(t_2 - t_1)/T_L] \tag{2}$$

where Lagrangian time scale represents the time over which the velocity of a particle is self-correlated. There is another time scale - Eulerian time scale (T_E) that represents the time the turbulent eddy pass through a fixed point. Normally Lagrangian time-scales are more difficult to measure as it requires making a measurement in the fluid frame of reference. Many models have been suggested to find the relation between Lagrangian and Eulerian time scales [23, 9, 10]. The Lagrangian time scales are related to the Eulerian time scales through the relation $T_L = \eta T_E$ where the Eulerian time scale, T_E, can be derived from the energy dissipation time scale, and η is assumed to be unity from other experimental results. Assuming that turbulence is homogeneous and isotropic the Eulerian time scale can be determined from the RANS model through the specific dissipation rate variable, ω, using the relation

$$T_E = \frac{1}{3}\frac{2}{C_\mu \omega} \tag{3}$$

where $C_\mu = 0.09$. Note, if we were to consider the inhomogeneity of turbulence in longitudinal, lateral, and vertical directions then the 1/3 factor would be replaced with an appropriately weighted set of coefficients for each of the corresponding directions. While the assumptions of homogeneity is satisfactory for near field simulations presented here,

non-homogeneity would need to be considered for more distant atmospheric transport predictions due to the inhomogeneity of the ABL.

Next term to be modeled in equation(1) is the random vector $\mathbf{u}''$. It is assumed that $\mathbf{u}''$ follows normal distribution of

$$\mathbf{u}'' = \frac{1}{\sqrt{2\pi\sigma_{\mathbf{u}''}}} exp(-\frac{x^2}{2\sigma^2_{\mathbf{u}''}}) \tag{4}$$

where $\sigma_{\mathbf{u}''}$ is the standard deviation of the velocity components, characterized by

$$\sigma_{\mathbf{u}''} = \sigma_{\mathbf{u}'}\sqrt{1 - R_L^2(t_2 - t_1)} \tag{5}$$

where $\sigma_{\mathbf{u}'}$ is the standard deviation of $\mathbf{u}'$, defined as

$$\sigma_{u'} = \sqrt{\frac{2}{3}k} \tag{6}$$

where k is the turbulent kinetic energy.

3 Modeling Dust Emissions

For the purpose of simulating the near-field generation and transport of dust we need models for the quantity of dust emitted, the location of the emissions, and the particulate size distribution of the emissions. The overall mass flux of particles emitted from a moving vehicle have been relatively well characterized by a number of

studies[30, 8, 7, 32, 13, 11, 17] which characterize the total emissions from vehicle traffic (suitable for use in line source models) based on various factors such as vehicle speed and weight, soil silt content, and soil moisture content. These studies do not provide localized information about the distribution of dust, but studies have shown that the total dust concentrations for particles smaller than 10 microns remain relatively unchanged over distances on the order of 1 kilometer provided that the terrain is relatively open[32]. Field studies show that the quantity of dust emission depends on the parameters that characterize the condition of the road (e.g. soil silt content, moisture content), vehicle features (e.g. vehicle weight, vehicle speed, number of wheels) and the climate conditions (e.g. frequency and amounts of precipitation). Silt content refers to the mass of silt-size material (equal to or less than 75 μm in physical diameter) per unit area of the travel surface. The downwind dust emission measurements in emission models were usually made 5 meters from the road. Emission factor (EF) is usually the value that is modeled in dust emission models, and it is usually expressed as the weight of dust divided by the unit weight, volume, distance, or duration of the activity that emits the dust. For air quality modeling the EPA model AP-42[28] is often utilized to model particle sources due to vehicle traffic on unpaved roads. We also utilize the AP-42 model to characterize the bulk mass flux of particle emissions. We combine this global model with a model of local mass emission to construct a near field dust emission model. The components of this model are outlined in the following subsections.

3.1 The EPA AP-42 Model

We adopt the emission model documented in AP-42[28] which is a primary compilation of emission factor information from comprehensive studies conducted by the U. S. Environmental Protection Agency (EPA) over last few decades. The models were developed using multiple linear regression analysis of EF test data versus parameters that affect the amount of particle emissions. Although the emission factor model for unpaved road has been modified over the past 20 years, all versions have important common features. The silt loading has consistently been found to be the most important factor in emission models. In this study, we use 2003 version of AP-42 emission factor model that was developed through a collection, selection and analysis of data from 12 field test reports on dust emission induced by vehicles traveling on unpaved roads, as shown in eqn. (7).

$$EF = \frac{k(s/12)^a(W/3)^b}{(M/0.2)^c} \tag{7}$$

where EF = Emission factor, pounds per vehicle-mile-traveled, (lb/VMT)

k = Particle size multiplier (dimensionless)

s = Silt content of road surface material (%)

W = Mean vehicle weight, ton (ton)

M = surface material moisture content (%)

For air quality purposes the particulate emissions are characterized into three size

Table 1: Parameters for eqn. (7)

constant	$PM_{2.5}$	PM_{10}	PM_{30}
k	0.38	2.6	10
a	0.8	0.8	0.8
b	0.4	0.4	0.5
c	0.3	0.3	0.4

classifications of particle matter (PM) known as PM_{30}, PM_{10}, and $PM_{2.5}$ which represent all particle matter that has a diameter less than 30, 10, and 2.5 micrometers respectively. The particle size multiplier, k for different size range for eqn. (7) is given in table 1.

Note that "normalizing factors" of 12 percent silt content and 3 kilogram vehicle weight are used in both models. 0.2 percent soil moisture content is selected as the reference moisture content in eqn. (7), which is usually considered as the default dry condition moisture content. The moisture content is influenced by meteorological and physical parameters that varies with time and location. According to AP-42, the overall mean moisture content in publicly accessible road data set was 1.1 percent. The moisture content for the desert ranges from 0.17 to 0.48 percent. Soil silt content has significant effect on dust emission factors. A summary of values of silt content on industrial and public roads is given in table 13.2.2-1 in AP-42 [28]. Mean silt contents for gravel roads and dirt roads were found to be 6.4 percent and 11 percent respectively. Note for these models to remain consistent with experimental conditions, mean wind speed should range between 4 to 20 MPH.

3.2 Localized Mass Injection Models

The EPA AP-42 model provides a reasonable model of the bulk of particulate matter that is emitted due to vehicle travel (at uniform speed on a unpaved road surface), however it provides no information about where the emissions emanate from a vehicle. For our simulations we are interested in the detailed transport of particulate matter around the geometry of the vehicle and for this we need to know the actual locations of emissions. Generally emissions will come from three sources: 1) directly from the contact points (e.g. tires or tracks) of the vehicle with the dusty surface, 2) saltation processes caused by impacts of emitted particles with the surface, and 3) particles liberated due to the action of shear of the air flow created by the vehicle motion. For dusty unpaved road surfaces we assume that the majority of dust is emitted directly from contact points rather than from saltation and shear processes, which appears to be the case from simply observing vehicles traveling on unpaved roads.

For the contact point emissions, there appears to be two primary mechanisms for emission: 1) surface adhesion and shear with the ground cause particulates to stick to the tire or track which are then emitted due to centrifugal force as the tire/track rotates up from the ground, and 2) crushing action at the leading edge of the tire/track causes particles to be ejected at the leading edge. Unfortunately, from the literature search, we have not found any experimental data that provides localized information about emissions such as the relative quantity of particulate matter emitted from these localized regions. Lacking quantitative data, we have created a model that qualitatively

produces dust plumes near the tires that are similar to observation.

In our emission model we assume that emissions come from the tire tread surface and we assign a probability of emission as a distribution over the tire. In this model we describe the tire contact with the ground according to the schematic diagram shown in figure 1. We compute an emission probability based on the angle of the tire tread surface normal with respect to the coordinate system formed by the axle vector (into the page) and the gravitational force vector. If the surface normal points within 10 degrees of the axle vector, it is assumed that this is part of the tire sidewall and the emission probability is set to zero. Otherwise the probability is set by the angle θ as shown in figure 1. The non-normalized emission probability is given by the equation

$$\xi = \epsilon * (\max\{\cos\theta, 0\})^{\eta} \tag{8}$$

where ϵ is an efficiency factor that is used to scale the emissions between the leading and trailing points of contact, and η is a parameter that describes the localization of emissions. The maximum function prevents emissions from occurring on the top of the tire. The efficiencies, ϵ, and localization parameter, η for the trailing contact point (where θ is positive) is set to $\epsilon_t = 0.9$ and $\eta_t = 2$, while the leading contact point (where θ is negative) is set to $\epsilon_l = 0.1$ and $\eta_l = 6$. With these settings, 90% of the emissions come from the trailing point of contact, while the leading point of contact has a distribution of emissions that is heavily biased towards the ground region. The probability distribution function is formed by normalizing ξ by the integration of ξ

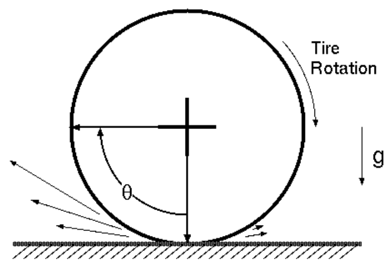

Figure 1: Schematic of Tire-Ground Contact

over the tire surface. Particles are assumed to be emitted from this surface with the tangential velocity of the rotating tire. We use this model to describe where the localized emissions of the AP-42 model emanate from in the vehicle mesh, while the overall mass flux is adjusted to meet the AP-42 model for vehicle dust emissions.

3.3 Qualitative Evaluation

Before we begin validation, we perform a simulation of a moving vehicle to determine if the model produces qualitatively reasonable results. For this test case we consider the simulation of a Nissan Pathfinder SUV for which geometry was already available to evaluate the simulation of dust transport for a realistic configuration. For this simulation we utilize the Loci/CHEM solver using a 15 million cell viscous mixed element mesh that as generated by the SolidMesh/AFLR3 mesh generation software[15].

For the simulation of particle generation and transport, we have the SUV traveling with 13.5m/s (about 30MPH) uniform forward velocity with a cross wind of 6.75 m/s (about 15MPH). The wind is simulated as an ABL with a velocity of 6.75m/s at one

meter height using a surface friction velocity of $u_\star = 0.6m/s$ and roughness length of $y_0 = 0.01m$. The rubber part of the tire is prescribed a rotational velocity 348.42 RPM which is consistent with a forward velocity of 13.5m/s. The rotation of the spokes of the hub is not considered in this model. Particles having a material density of quartz (2648 kg/m^3) are emitted using log-normal particle size distribution with particle mean diameters of $30\mu m$ and a variance of $\sigma = 0.25$. The BSL turbulence model and the first order stochastic turbulent dispersion model are employed in the simulation. Initial dust mass flux released by tires is determined using model described by eqn.(7). The silt content and soil moisture content are set to the default value, namely 12%, and 0.2% respectively. The weight of vehicle is taken from Nissan Pathfinder, which is $4500kg$. The mass flux computed from the model is then equally distributed to the 4 wheels. Particles are ejected from the tires using the localized mass injection model represented by eqn.(8).

Side and top views of the simulated dust distribution around the vehicle for this case are shown in figure 2. The vehicle surface and ground are shaded by gage pressure contours. Instead of viewing particles as points, we use the volume visualization method in which the computed particle concentration field is averaged over the volume in time allowing the particle cloud to be viewed as a semi-transparent region to mimic the scattering effects that visually dominate particle plumes. From this figure it can be seen that the localized release model of particles produces a distribution of dust both around the tires and the vehicle that follows qualitative expectations (*e.g.* the simulated

particle cloud looks similar to what is observed when a vehicle drives down a dusty road). Particles are initially released near the tire contact points and are then entrained by the recirculating flows in the vehicle wake and scattered by both the wake and atmospheric turbulence. The structure of the mean wake of the vehicle is not strongly evident because turbulent dispersion plays a role on scattering the particles. Note, that since the stochastic model does not include any spatial correlations, there is no billowing type of effect. Each particle follows its own "Brownian Motion" type of trajectory, but a group of particles in the same region of space do not follow the same "eddy" and the overall effects are averaged out to give an average characterization of the particle plume. In general, these results show that the described model performs in a fashion that is qualitatively comparable to the observed dusty cloud produced by vehicles traveling on unpaved surfaces.

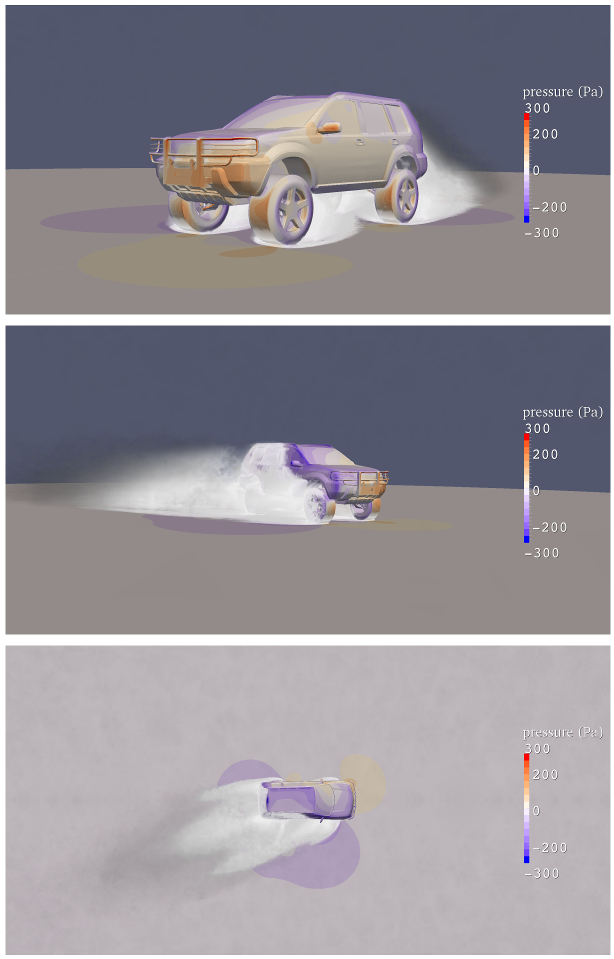

Figure 2: Dust distribution around the moving vehicle from views on front driver's side (top), front passenger side (middle) and top (bottom) with volume visualization

4 Model Validation Case

In order to validate the model we would like to compare to experimental data that is as close to the vehicle as possible in order to better validate near field particle distributions. Unfortunately, most experimental data are collected at some distance from the vehicle since their purpose is to validate environmental quality models that treat dusty roads as line sources. After reviewing the available literature, we have determined that measurements of dust concentrations carried out by Veranth *et.al* [32, 5] provide the most appropriate data for our validation needs. The main reason we chose this data set is that there are measurement data conducted at 3 meters away from the road, while other measurements from our literature survey were performed at much greater distances. In addition, the data presented in these experiments included absolute measurements of dust concentrations that are suitable for validation exercises, instead of relative measurements that were designed to calibrate existing models. Finally, compared to other experimental work, the running conditions in this field study were relatively well documented which improves the suitability of this data set for validating our detailed near-field models.

4.1 Outline of Experimental Data Set

The field measurements were conducted at the Dugway Proving Ground, Tooele County, Utah by University of Utah in collaboration with the Mock Urban Setting Test(MUST). The original purpose of this study was to investigate the significance of near-source

removal of the dust under the stable atmosphere and high surface roughness conditions. Surface roughness that might be presented by large surface roughness like buildings was modeled in the experiment by a 10 by 12 array of 2.5m high, 2.4m wide, and 12.2 long rectangular cargo shipping containers. In the surrounding landscape, vegetation is a thin cover of brush of 0.5-1m high. The soil was classified by the Natural Resources Conservation (2000) as Skumpah silt loam and had 16% silt content. The atmospheric condition was stable. The test was performed using a 1994 Ford pickup truck with $3900kg$ weight that was driven at the speed of $9m/s$ on an $180m$ length of unpaved road that ran parallel to the upwind edge of the container array. Wind speed was normally between 1 and $5m/s$ and the wind direction remained within 45 degree perpendicular to the road. Table 2 shows the measured wind speed at different height with standard deviation averaged within 1.5 hour test period. Average air temperature and pressure were $294K$ and $0.855atm$ respectively.

Table 2: Mean and standard deviation wind speed for 1.5 hour test period

Height(m)	Upwind wind speed (m/s)
4	3.42 ± 0.51
8	4.07 ± 0.50
16	4.72 ± 0.52

Dust concentration was measured using DustTrak analyzers with PM_{10} inlets. The instruments were mounted on a movable tower at various heights to collect the data at different location. As we are interested in the near-field predictions, we focus only on the near-source tower location which is located 3 meters from the edge of the road, or

4.5 meters from the road center-line. Dust measurements were performed on the tower at heights of 0.9, 1.7, and 3.7 meters above the ground. The vehicle was traveling for total 1.5 hours as a series of 44 trips at 1-1.5 minute intervals, and the time-averaged dust concentration was recorded every 5 seconds. Peak concentration value for each trip (mg/m^3) and pulse area defined as the time integrated concentration per trip (mgs/m^3) were recorded in the experiment and are provided in table 3.

Table 3: Mean and standard deviation of dust concentration data at near source (3 meters from the road)

Height(m)	peak concentration (mg/m^3)	pulse area (mgs/m^3) per trip
0.9	38.9 ± 21	302 ± 171
1.7	19.9 ± 11	144 ± 92
3.7	10.3 ± 7.2	77.8 ± 56

4.2 Simulation Setup

For the simulation setup we perform simulations in the vehicles reference frame. In this reference frame, the tower moves through the domain at the rate of the vehicle speed, and we can obtain the time history of the tower particle concentrations by plotting the concentration along a line that represents the measurements at a given tower height. In this plot, distance along the line can be converted into time in the tower's reference frame simply by dividing by the vehicle speed. Thus we have a straightforward way to compare simulations to measured experimental data provided that the simulation domain is large enough that the entire pulse of the particle plume is recorded within

the domain. The first step in this process is the generation of a mesh for a long domain that included the vehicle and enough downwind region to properly simulate the plume's intersection with the measurement tower. In the experiment, a 1994 Ford pickup truck was used as the dust emission source. For the geometry of the 1994 Ford pickup we constructed a simplified model based on general vehicle geometry available in generic descriptions from Ford including vehicle wheel-base, bed dimensions, and cab height. Figure 3 shows the resulting simplified pickup truck geometry. To determine the sensitivity of the dust plume at the first tower location to the vehicle geometry we ran simulations using the detailed Pathfinder SUV and the approximate pickup truck geometry and found that there were not significant differences in the simulated dust plume at the 3 meter tower location. This is not surprising as it confirms observations in the work of Gillies *et.al* [8] that showed that the size of the wake created by a moving vehicle was dependent on the height of the vehicle. In our study, the heights of SUV and pickup truck is about the same, namely 1.7m and 1.9m respectively. From these studies we conclude that the simplified geometry of the pickup truck is sufficient for validating to the tower data that is 3 meters from the edge of the road.

The experimental data setup that we are using for validation included an array of cargo containers that were placed about 6 meters from the road with the first dust tower being just 3 meters away from the road edge. Although the dust tower is upwind of the container array, the effect of the blockage represented by the container array will cause an uplifting flow caused by the blockage of the array. To correctly capture the effects of

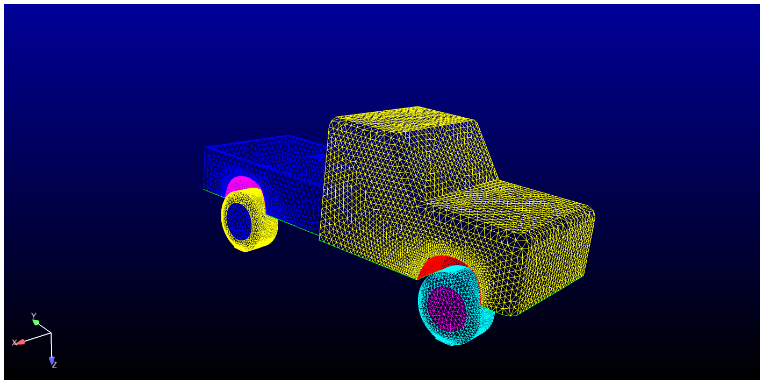

Figure 3: Geometry and surface mesh of a Ford Pickup truck

the container array in our validation, we create a rectangular block with the same height of the containers ($2.5m$) located at $6m$ from edge of the road (distance is estimated from the schematics given in the report[32]) and extending along the road throughout the domain as shown in figure 4. The measurement tower is placed half way between the blockage and the edge of the road. Simulations that we have performed comparing dust plumes with and without this blockage showed that it contributes a significant effect in the height of the dust plume at the closest measurement tower. In our simulation we approximate the container array as if it is a continuous obstruction along the road which approximates the blockage effect of the containers while also facilitating a simple steady-state simulation procedure.

For particle surface interactions we assume that any particle that interacts with the vehicle surfaces or with the ground rebounds specularly off of the surface. Although some particles will be removed on contact with the ground, empirical evidence suggests

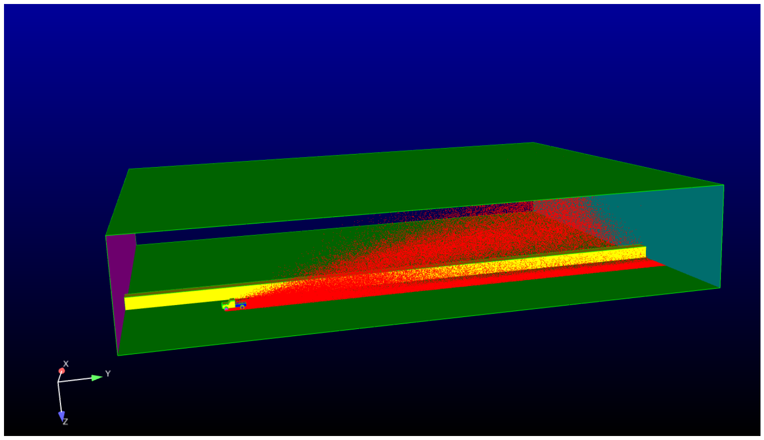

Figure 4: Computational domain with a blockage parallel to the vehicle traveling direction. Yellow part is the blockage, and particles are represented by red color

that in the near field only a very small amount of particles will be removed from the simulation by way of deposition. Therefore, we simply assume that no particle deposition occurs on these surfaces. For simulations over larger distances, a proper ground deposition model may be required to properly consider ground particle interactions.

Dust is emitted from the tires with a distribution that is described by equation (8) with the mass emission equally distributed to the four tires. The total mass flux of the tire emissions are determined by the AP-42 model as described by equation(7). The parameters of 16% silt content, $3900kg$ vehicle weight, 0.2% moisture content with particle size multiplier from PM_{10} were input to the eqn.(7) to get dust emission factor. This value combined with the vehicle speed of $9m/s$ gives $0.0096kg/s$ total mass flux injected from each of the four tires. A model for the distribution of the particle sizes is

prescribed by a log-normal distribution with a mean particle size of $10\mu m$ with standard deviation of 0.35.

To simulate the atmospheric wind effects, a background atmospheric wind profile is prescribed using logarithmic law as follows:

$$u = \frac{u^\star}{K} ln(\frac{z + z_0}{z0}) \tag{9}$$

where $K = 0.4$, and friction velocity ($u^\star$) and roughness height (z_0) are estimated to fit the upwind data within the variation of measurements listed in table 2. $u^\star = 0.24m/s$ and $z_0 = 0.01m$ are selected in the wind profile expression. The value of friction velocity agrees with field measurement of $u^\star$ from sonic anemometer data ($u^\star = 0.23m/s$) very well. Figure 5 demonstrates that the prescribed wind speed profile compares well with experimental data. As mentioned in field study, wind direction was within 45 degrees perpendicular to the road, but there was no data on average wind direction. In our simulation, the wind direction was first set perpendicular to the road, then 45 degrees to the road to evaluate the bounding effects of wind direction in the validation.

4.3 Validation Results

Simulations for two different wind directions ($90°$ and $45°$) were conducted for comparison to experimental data at the closest tower location. The dust concentration temporal history for each of the three tower sampling heights (0.9, 1.7, and 3.7 meters)

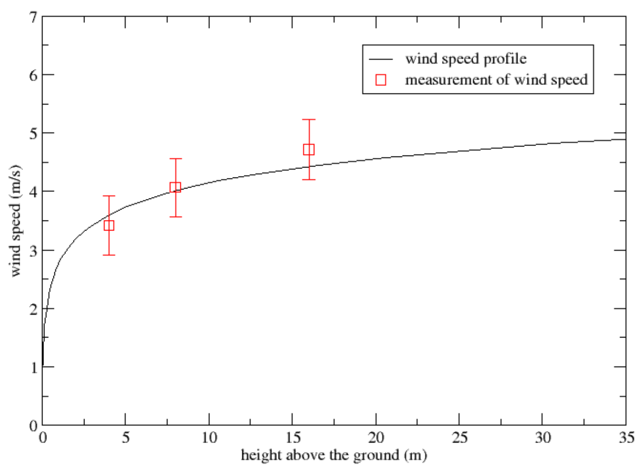

Figure 5: Comparison of prescribed atmospheric boundary layer profile and experimental data with variation of measurement

were determined from the steady state simulation. These tower heights are represented in the figure 6 showing three lines that represents the three sampling heights drawn on a cutting plane located at the tower location. From these spatial lines a temporal history can be reconstructed as shown in figure 7. Integrating the temporal histories we determine the peak and integrated concentrations of particles at each of the tower heights for comparison with experimental data as is shown in table 4.

The simulated peak dust concentration compare reasonably well with experimental data and are generally with experimental error bounds. We note that the wind direction used in the simulation has a significant impact on the resulting dust distribution at the tower location. In general, the simulations at the larger wind angle appear to be more consistent with the experimental data, and the simulations appear to under-predict integrated dust concentrations suggesting that perhaps more particles should have been emitted from the vehicle tires. In addition, it appears that the experimental results showed a slightly more dispersed particle plume than the simulation, in particular when observing the comparison of the integrated particle concentrations at the highest tower sampling location. However, our simulations are still within the experimental error bounds and so no definitive conclusion can be made. From this simulation, it is also clear that the wind characterization is a significant source of variability in the measured and simulated data, thus contributes uncertainty in the process of validation/calibration.

As already mentioned, numerical studies showed that details of the vehicle geometry did not play a significant factor in the measured dust plume. In addition we performed

Table 4: Comparison of dust concentration results between CFD simulation and experiment at closest tower (3m from road) with perpendicular and 45° simulated cross winds

Height (m)	measured peak concentration (mg/m^3)	simulated peak concentration (mg/m^3)		measured pulse area $(mg\ s/m^3)$	simulated pulse area $(mg\ s/m^3)$	
		90°	45°		90°	45°
0.9	38.9 ± 21	52.2	31.0	302 ± 171	116.	98.8
1.7	19.9 ± 11	48.0	26.0	144 ± 92	94.0	84.6
3.7	10.3 ± 7.2	10.1	7.51	77.8 ± 56	17.0	27.6

a number of additional simulations to determine the effect of other factors that may effect comparisons to the numerical experiments. The first consideration is the effects of the size distribution of the emitted dust particles. For the dust size distribution the amount of dust in the different categories can be inferred from the EPA model which provides different coefficients for $PM_{2.5}$, PM_{10}, and PM_{30} dust size categories. From this we inferred both the corresponding log-normal and Weibull size distribution PDFs and compared simulations using either log-normal (as used in the presented results) and the Weibull distribution which had a stronger bias towards small particle sizes. We found that there was no significant difference in the measured dust plume between these two PDF's suggesting that particle sizes played a minor role in the plume dispersion at the nearest tower. In addition, we evaluated the effects of the exponent on the localized dust emission model given in eqn. (8) by comparing a linear distribution ($\eta = 1$) instead of the square law used in the validation study. In terms of the plume shape observed at the 3 meter tower location, changes in the tire release model did not significantly change

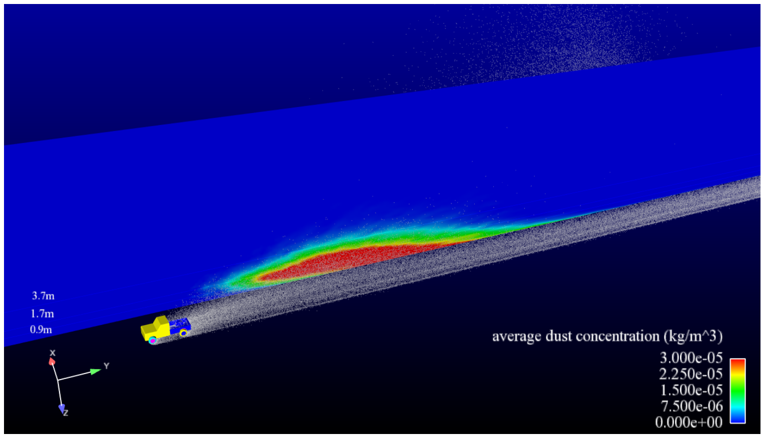

Figure 6: Dust distribution on the near source plane (3m from the road)

the dust distribution. However, the exponents that we used in the study produced a dust plume that better matched the qualitative character of tire emissions observed from vehicles moving on dusty roads.

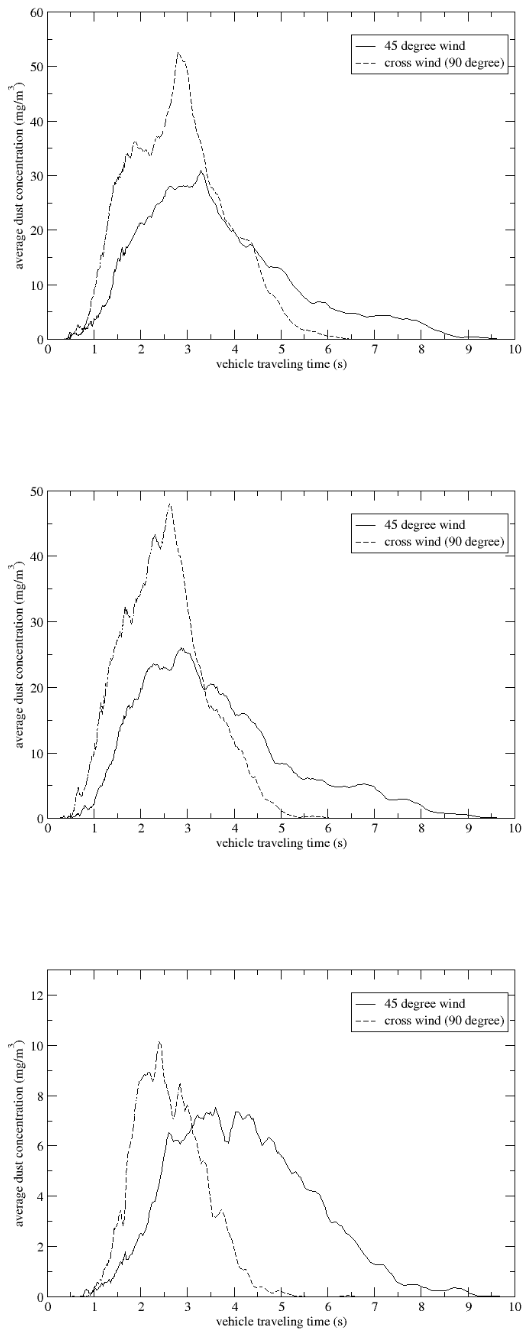

Figure 7: The simulated dust concentration pulse for different wind direction at 0.9m (top), 1.7m (middle) and 3.7m (bottom) measuring stations.

5 Concluding Remarks

Many aspects of vehicle functionality depend on the emission and transport of fugitive dust caused by vehicle movement, especially when traveling on unpaved surfaces. Given the needs for particle emission models, there are very few detailed models of the fugitive dust in the vehicle near-field region. In this paper we presented a modeling approach for fugitive dust emissions that can capture near-field dust concentrations. We validated this model by comparing simulated plumes at 3 meter towers with experimental data and found that the proposed model performed within experimental error bounds. This work also provided the first attempt to validate the numerical models for the near field dust emission and transport around a moving vehicle.

One unambiguous finding of literature review and our simulation studies is that current publicly available experimental data is inadequate to fully validate near-field dust emission and transport models. Most experimental data was commissioned to support atmospheric dust transport modeling for environmental quality impact studies. Basically these experimental studies were targeting data that is assumed to be averaged over time periods in the range of weeks to months, and over length scales on the order of kilometers or greater. As a result, most of these studies did not provide definitive data on the dust in the local area of the vehicle in the time-scale of a single traversal of a dusty terrain. Lacking detailed experimental data on the vehicle spatial and temporal scales, the ability to refine models beyond what is presented in this study is somewhat limited: while more sophisticated modeling approaches could be suggested, there would

be no way to provide sufficient validation of these models based on data available in the literature. Therefore, further enhancement of these models must proceed along with detailed experimental work focused on near field measurement of fugative dust emission on the appropriate time and space scales that would accurately capture localized dust behavior.

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References

[1] SERDP Project SI-1400, still active.

[2] Chen, J., Fu, X., and Wegman, E. Real-time simulation of dust behavior generated by a fast traveling vehicle. *ACM Transactions on Modeling and Computer Simulation 9*, 2 (1999), 81–104.

[3] CHEN, J., WEGMAN, E., AND WANG, J. Animation of dust behaviors in a networked virtual environment. In *6th International Conference in Central Europ on Computer Gaphics and Visualization* (Feb. 1998), pp. 487–494.

[4] CUSCINO, T., HEINSOHN, R., AND BIRNIE, C. Fugitive dust from vehicles traveling on unpaved roads. In *Proceedings of the conference on metroplitan physical environment* (1977), G. Heisler and L. Herrington, Eds., pp. 295–302.

[5] ETYEMEZIAN, V., GILLIES, J., HUHNS, H., NIKOLIC, D., WATSON, J., VERANTH, J., LABEN, R., SESHADRI, G., AND GILLETTE, D. Field testing and evaluation of dust deposition and removal mechanisms: Final report. Tech. rep., DRI, Las Vegas, NV for the WESTAR Council, Lake Oswego, OR, January 2003.

[6] GILLIES, J., ARNOTT, W., ETYEMEZIAN, V., KUHNS, H., MOOSMULLER, H., DUBOIS, D., ABU-ALLABAN, M., SCHWEMMER, G., AND GILLETTE, D. Characterizing and quantifying local and regional particulate matter emissions from department of defense installations. Tech. rep., DRI and NASA and NDAA, March 2005. SERDP Project CP-1191.

[7] GILLIES, J., ETYEMEZIAN, V., KUHNS, H., MMSMULLER, H., ENGELBRECHT, J., KING, J., UPPAPALLI, S., NIKOLIC, G., MCALPINE, J., ZHU, D., SKIBA, M., AND GILLETTE, D. Particulate matter emissions factors for dust from unique military activities. Tech. rep., DRI, 2010. SERDP Project SI-1399.

[8] Gillies, J., Etyemezian, V., Kuhns, H., Nikolic, D., and Gillette, D. Effect of vehicle characteristic on unpaved road dust emissions. *Atmospheric Environment 39* (2005), 2341–2347.

[9] Hanna, S. Lagrangian and eulerian time-scale relation in the daytime boundary layer. *Journal of Applied Meteorology* (1980).

[10] Kos, I., Belusic, D., Jericevic, A., Horvath, K., Koracin, D., and Prtenjak, M. Education and research: Initial development of the atmospheric lagrangian particle stochastic (alps) dispersion model. *GEOFIZIKA 21* (2004), 37–52.

[11] Kuhns, H., Gillies, J., Etyemezian, V., Nickolich, G., King, J., Zhu, D., Uppapalli, S., Engelbrecht, J., and Kohl, S. Effect of soil type and momentum on unpaved road particulate matter emissions from wheeled and tracked vehicles. *Aerosol Science and Technology* (2010), 187–196.

[12] Lamb, R., and Duran, D. Eddy diffusivities derived from a numerical model of the convective boundary layer. *Nuovo Cimento 1c* (1977), 1–17.

[13] Langston, R., Jr, R. M., Etyemezian, V., Kuhns, H., Gillies, J., Zhu, D., Fitz, D., Bumiller, K., James, D., and Teng, H. Clark county paved road dust emission studies in support of mobile monitoring technologies. Tech. rep., DAQEM and DRI and UC, Riverside and University of Neveda, December 2003.

[14] Luke, E., and Cinnella, P. Numerical simulations of mixtures of fluids using upwind algorithms. *Computers and Fluids 36* (December 2007), 1547–1566.

[15] Marcum, D. Unstructured grid generation using automatic point insertion and local reconnection. In *The Handbook of Grid Generation*. CRC Press, 1998, pp. 1–18.

[16] Menter, F. R. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal 32*, 8 (August 1994), 1598–1605.

[17] Nicholson, K., Branson, J., Geiss, P., and Channel, R. The effects of vehicle activity on particle resuspension. *J. Aerosol Science 20*, 1425-1428 (1989).

[18] Nickling, W., and Gillies, J. Emission of fine-grained particulate from desert soils. In *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, M. Sarnthein and M. Leinen, Eds. Kluwer Academic Publisher, Dordrecht, 1989, pp. 133–165.

[19] Pardyjak, E., Speckart, S., and Veranth, F. Near source deposition of vehicle generated fugitive dust on vegetation and buildings: Model development and theory. *Atmospheric Environment 42* (2008), 6442–6452.

[20] Richards, P., and Hoxey, R. Appropriate boundary conditions for computational wind engineering models using the $k - \epsilon$ turbulence model. *Journal of Wind Engineering and Industrial Aerodynamics* (1993).

[21] Riddle, A., Carruthers, D., Sharp, A., and Stocker, J. Comparisons between fluent and adms for atmospheric dispersion modeling. *Atmospheric Environment 38* (2004), 1029–1038.

[22] Sawford, B. Lagrangian statistical simulation of concentration mean and fluctuation fields. *J. Climate Appl. Meteor 24* (1985), 1152–1166.

[23] Sethuraman, S., Meyers, R., and Brown, R. A comparison of a eulerian and a lagrangian time scale for over-water atmospheric flows during stable conditions. *Boundary-Layer Meteorology 14* (1978), 557–565.

[24] Shao, Y., Raupach, M., and Findlater, P. The effect of saltation bombardment on the entrainment of dust by wind. *Journal of Geophysical Research* (1993), 12719–12726.

[25] Shir, C. A preliminary numerical study of atmospheric turbulence flows in the idealized planetary boundary layer. *J. Atmos Sci. 30* (1973), 1327–1339.

[26] Succarieh, M. Control of dust emissions from unpaved roads. Tech. rep., University of Alaska, May 1992. Prepared for Alaska Cooperative Transportation and Public Facilities Research Program.

[27] Thomson, D. Criteria for the selection of stochastic models of particle trajectories in turbulent flows. *J. Fluid Mech 180* (1987), 529–556.

[28] US Environmental Protection Agency, Research Triangle Park, NC. *Emission Factor Documentation for Ap-42, uection 13.2.2, unpaved roads, final report*, 1998.

[29] US Environmental Protection Agency, Research Triangle Park, NC. *AP-42*, fifth ed. ed., 2003.

[30] US Environmental Protection Agency, Research Triangle Park, NC. *AP-42, Miscellaneous Source Chapter 13*, fifth ed. ed., 2003.

[31] Veluri, S., Roy, C., and Luke, E. Comprehensive code verification techniques for finite volume cfd codes. *Computers and Fluids 70* (November 2012), 59–72.

[32] Veranth, J., Pardyjak, E., and Seshadri, G. Vehicle-generated fugitive dust transport: analytic models and field study. *Atmospheric Environment* (2003).

[33] Walshe, J. *CFD Modeling of Wind Flow Over Complex and Rough Terrain*. PhD thesis, University of Loughborough, 2003.

[34] Wilson, J. Turbulent dispersion in the atmospheric surface layer. *Bound-Layer Meteor 22* (1982), 399–420.

[35] Zannetti, P. New monte carlo scheme for simulating lagranian particle diffusion with wind shear effects. *Appl. Math Modeling 8* (June 1984), 188–192.

[36] Zhang, Y., and Luke, E. Concurrent composition using Loci. *Computing in Science and Engineering 11*, 3 (May 2009), 27–35.